Deep Exclusive Meson Production at Jefferson Lab Hall C

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CAP Congress, Université de Montréal, May 27, 2013.

Fundamental questions in hadron physics

1950-1960: Does the proton have finite size and structure?

- Elastic electron-proton scattering
  - ⇨ the proton is not a point-like particle but has finite size
    - charge and current distribution in the proton, G_E/G_M

Nobel prize 1961- R. Hofstadter

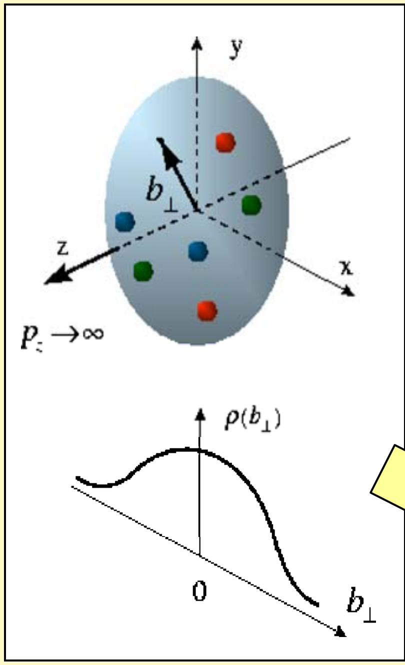
1960-1990: What are the internal constituents of the nucleon?

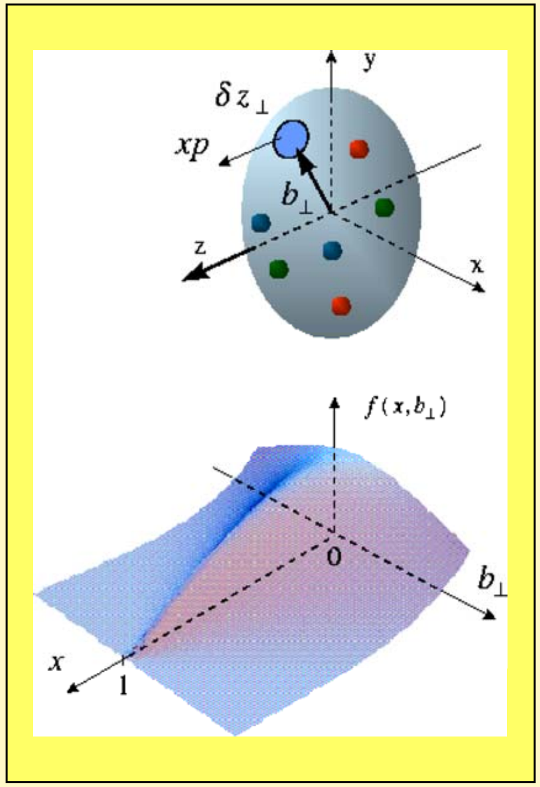
- Deep inelastic scattering
  - ⇨ discover quarks in 'scaling' of structure function and measure their momentum and spin distributions

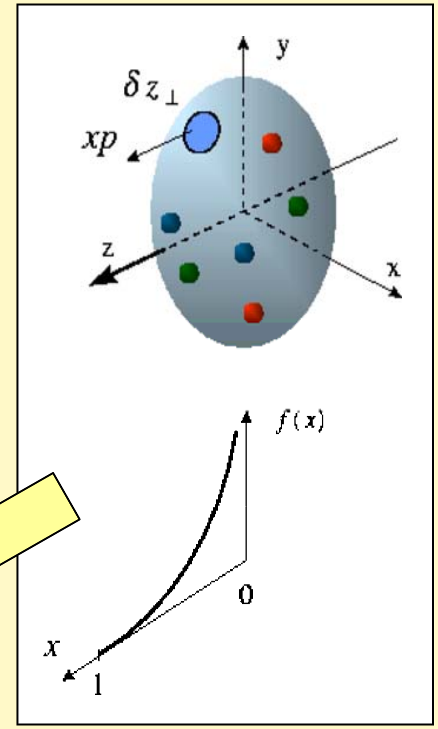
Nobel prize 1990 - J. Friedman, H. Kendall, R. Taylor

Today: How are the nucleon's charge & current distributions related to the quark momentum & spin distributions?

Beyond form factors and quark distributions – Generalized Parton Distributions (GPDs)







ELASTIC SCATTERING:
Proton form factors, transverse charge & current densities

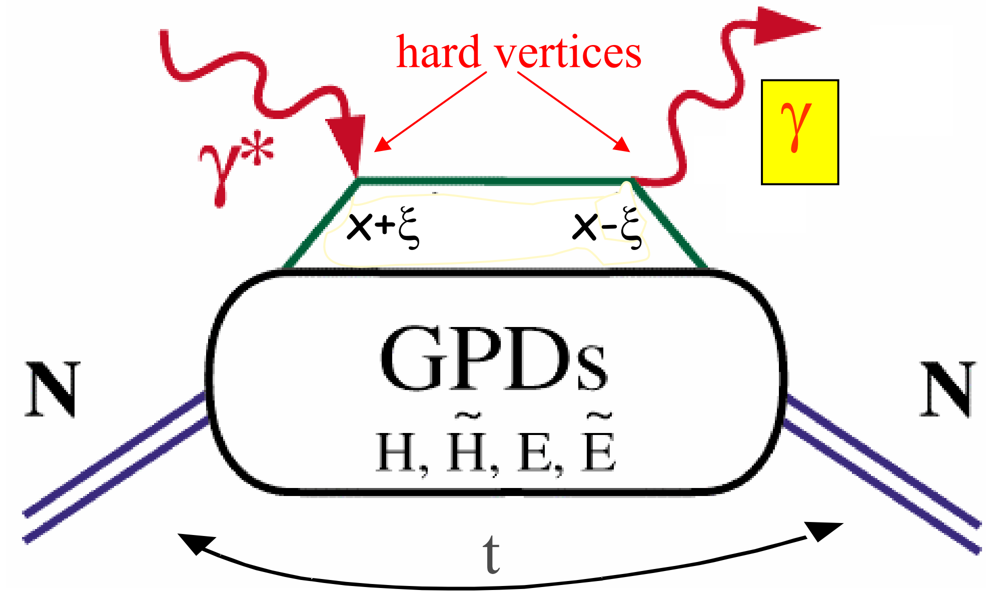
DEEP EXCLUSIVE SCATTERING:
Correlated quark momentum and helicity distributions in transverse space - GPDs

DEEP INELASTIC SCATTERING:
Structure functions, quark longitudinal momentum & helicity distributions

Explore GPDs via Deep Exclusive Processes

Reaction must proceed via "handbag" mechanism.

Deeply Virtual Compton Scattering (DVCS)



x – longitudinal quark momentum fraction

2ξ – longitudinal momentum transfer

$\sqrt{-t}$ – Fourier conjugate to transverse impact parameter

$H(x,\xi,t), E(x,\xi,t), \ldots$

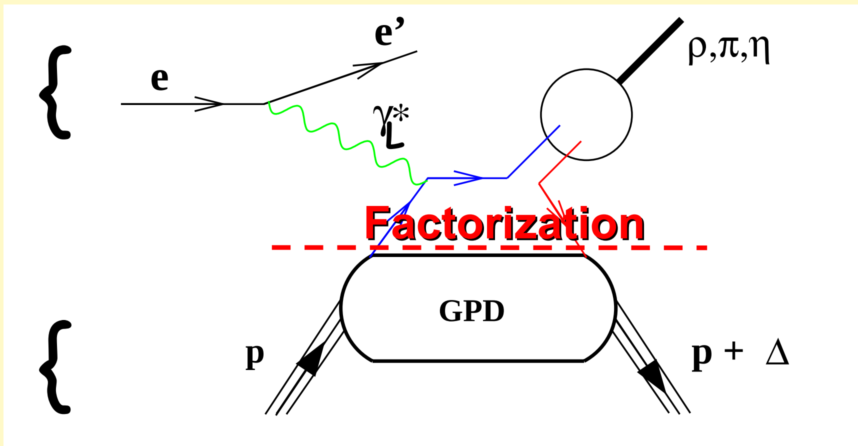
$$\xi = \frac{x_B}{2-x_B}$$

GPD Studies require Hard Exclusive Reactions

- In order to access the physics contained in GPDs, one is restricted to the hard scattering regime.
  - No single criterion for the applicability, but tests of necessary conditions can provide evidence that the Q^2 scaling regime has been reached.

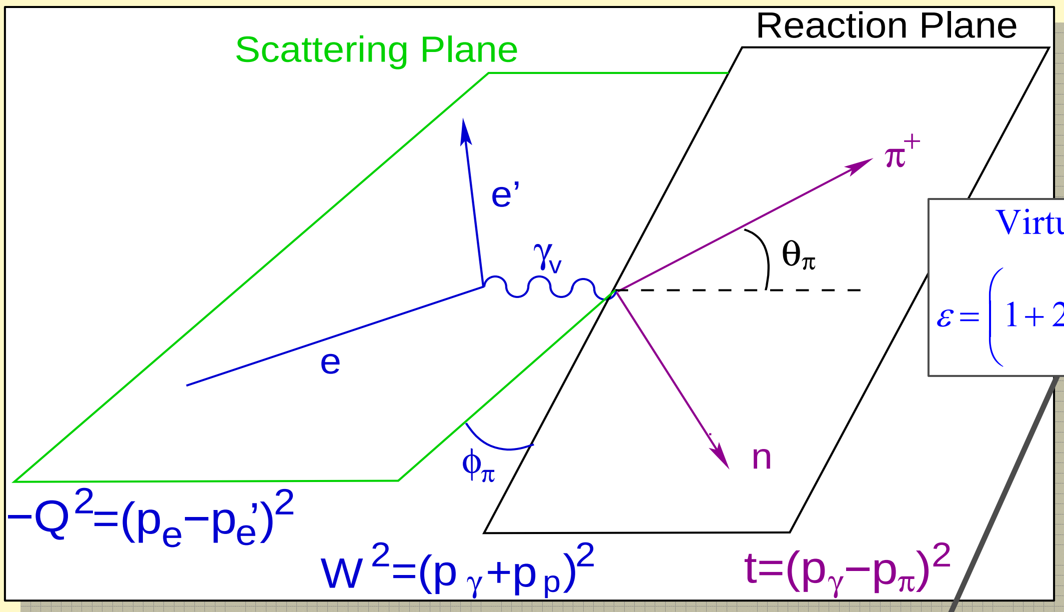
- **Factorization property of hard reactions:**

  - **Hard probe creates a small size $q\bar{q}$ and gluon configuration,**
    - **interactions can be described by pQCD.**
  - **Non-perturbative part describes how hadron reacts to this configuration, or how the probe is transformed into hadrons (parameterized by GPDs).**



GPD Studies require Longitudinal Virtual Photons

- Hard exclusive meson electroproduction first shown to be factorizable by Collins, Frankfurt & Strikman [PRD **56**(1997)2982].
- **Factorization applies when the γ^* is longitudinally polarized.**
  - **corresponds to small size configuration compared to transversely polarized γ^*.**

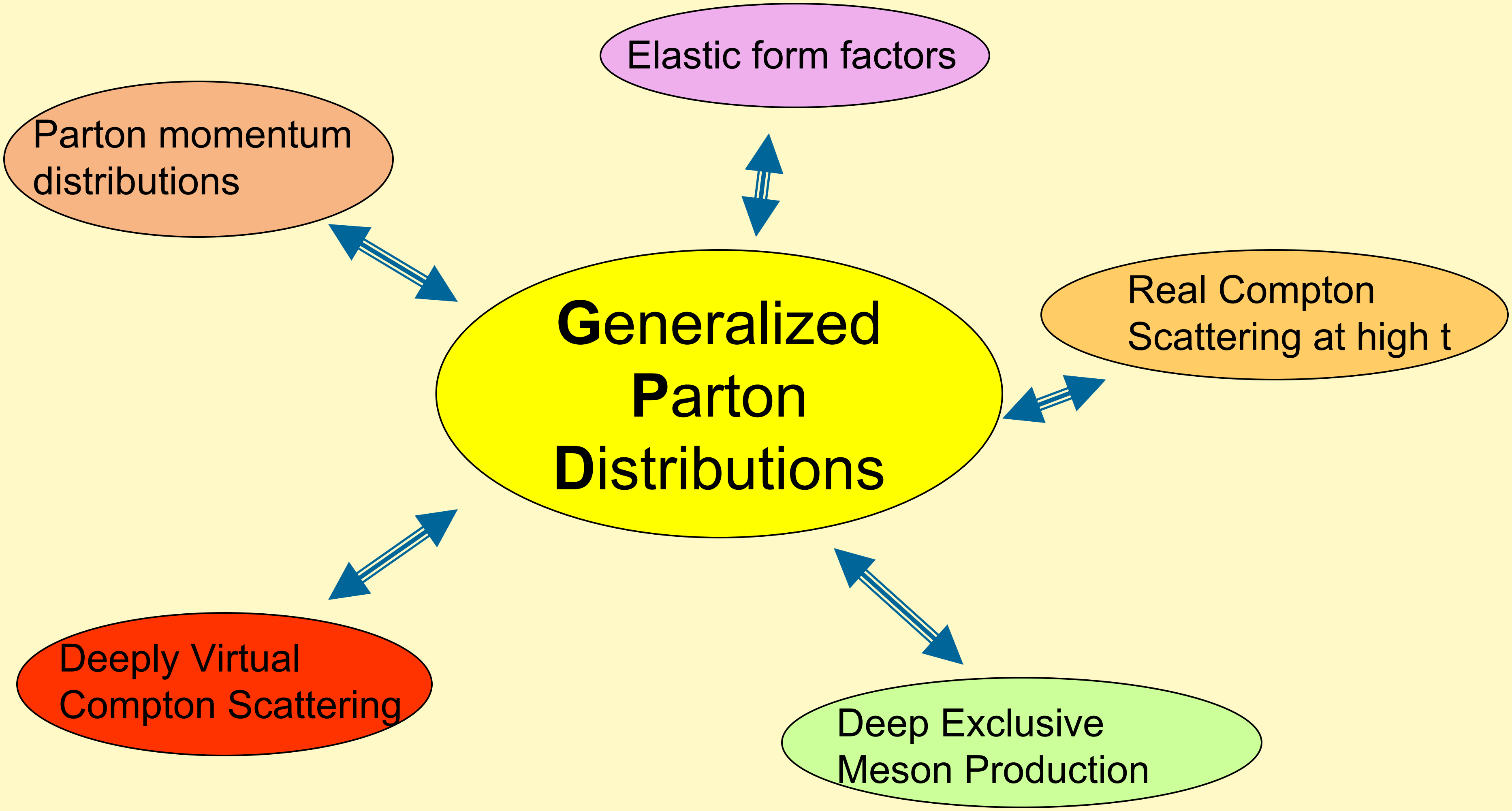


Virtual-photon polarization:

$$\varepsilon = \left(1 + 2\frac{(E_e - E_{e'})^2 + Q^2}{Q^2}\tan^2\frac{\theta_{e'}}{2}\right)^{-1}$$

$$2\pi\frac{d\sigma}{dt\,d\phi} = \varepsilon\frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon(\varepsilon+1)}\frac{d\sigma_{LT}}{dt}\cos\phi + \varepsilon\frac{d\sigma_{TT}}{dt}\cos 2\phi$$

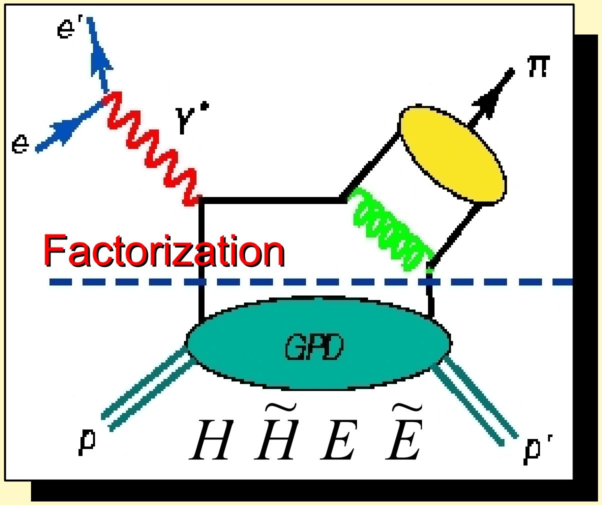
GPDs - A Unified Description of Hadron Structure



Applicability of the GPD Mechanism

- **Determining the bounds of the kinematic regime where the GPD mechanism may apply is a high priority for JLab 12 GeV.**
  - **GPDs can only be extracted from hard exclusive data where hard-soft factorization applies.**

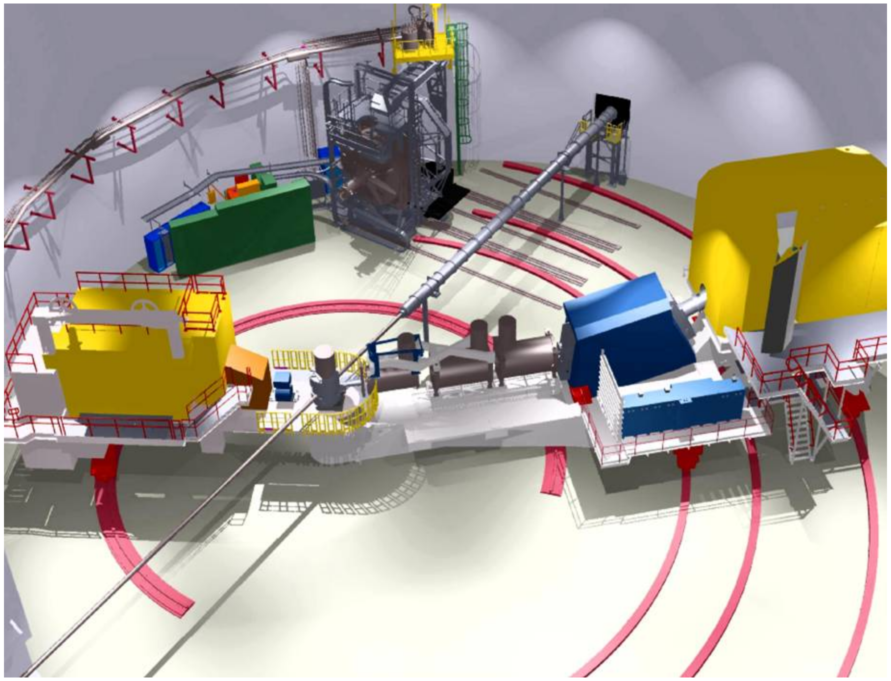
- One of the most stringent tests of factorization is the Q^2 dependence of the π^+ or K^+ electroproduction cross section
  - σ_L scales to leading order as $1/Q^6$.
  - σ_T scales as $1/Q^8$.
  - As Q^2 becomes large: $\sigma_L >> \sigma_T$.



- **Contribution of σ_T unknown at higher energies.**
- **Need to <u>experimentally demonstrate</u> $\sigma_L >> \sigma_T$ at higher Q^2**
  → not just assume it.
- **If transverse contributions are larger than anticipated, the accessible phase space for GPD studies may be limited.**

Upgrades to Experimental Hall C

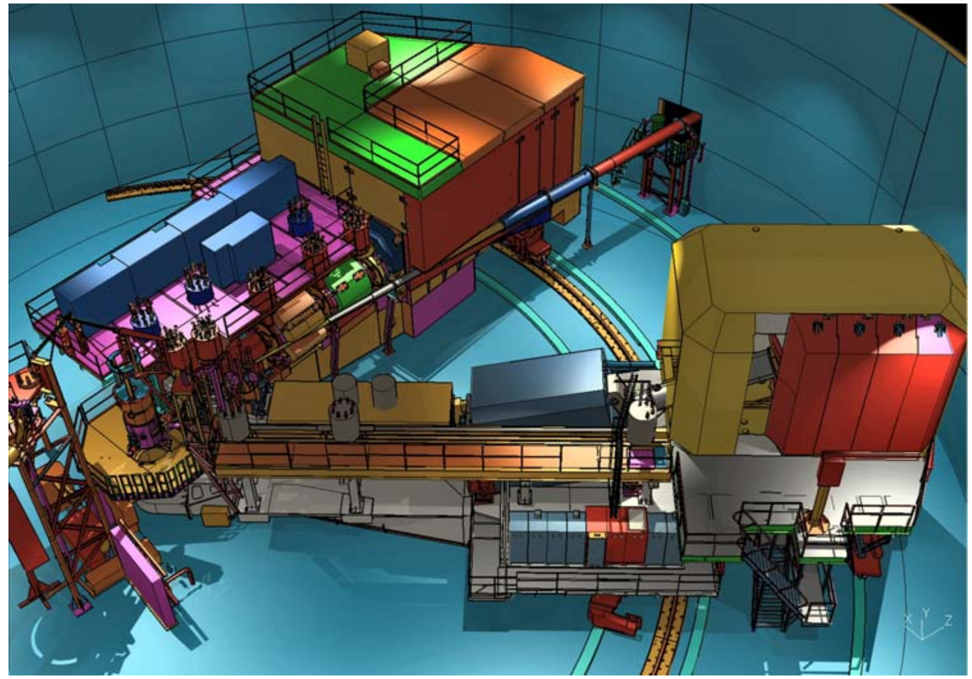
Standard 6 GeV Operation



Hall C's High Momentum Spectrometer, Short Orbit Spectrometer and specialized equipment for studying:

- The strange quark content of the proton.
- Form factors of simple quark systems.
- The transition from hadrons to quarks.
- Nuclei with a strange quark embedded.

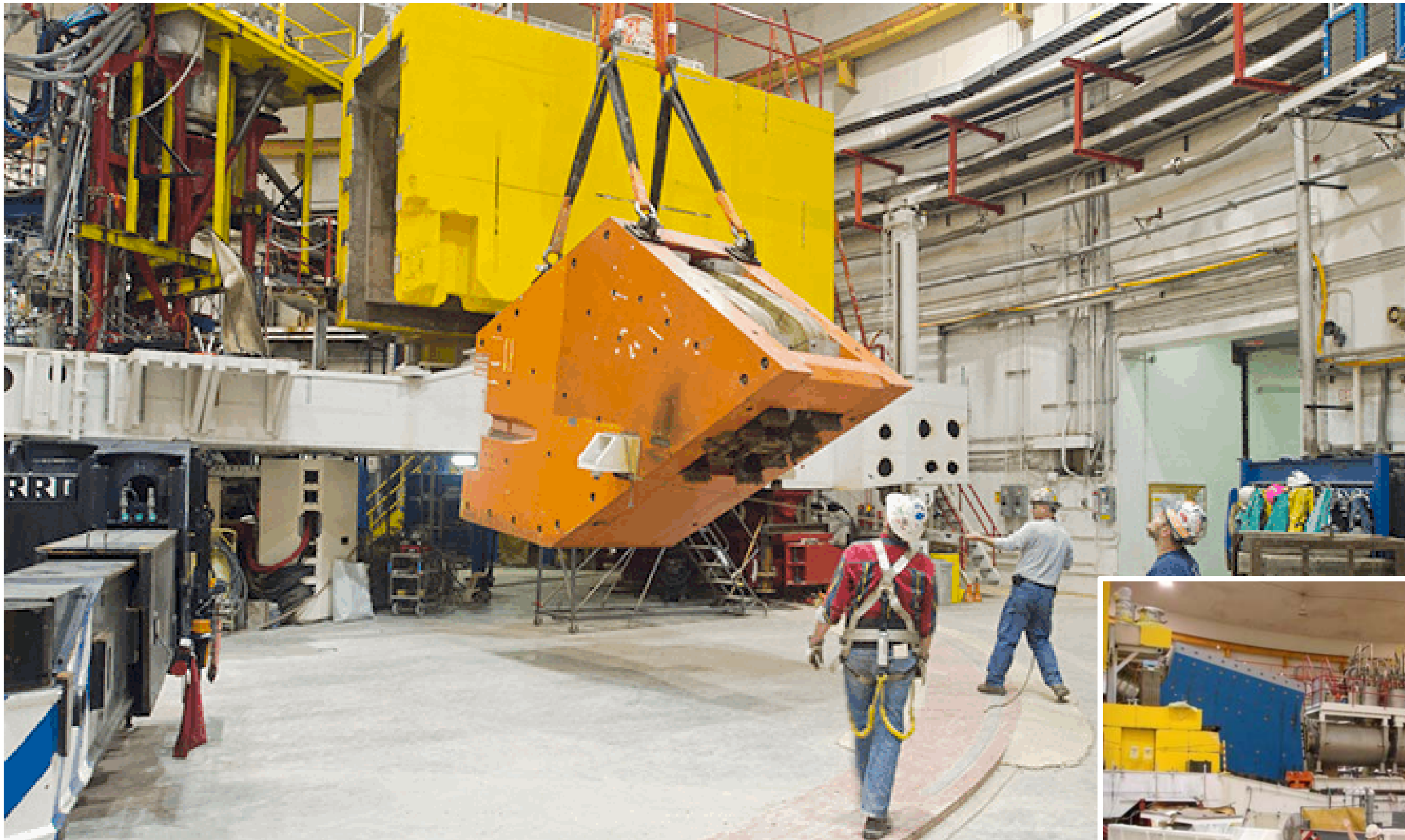
Future 12 GeV Operation



Add a Super- High Momentum (11 GeV) Spectrometer for studying:

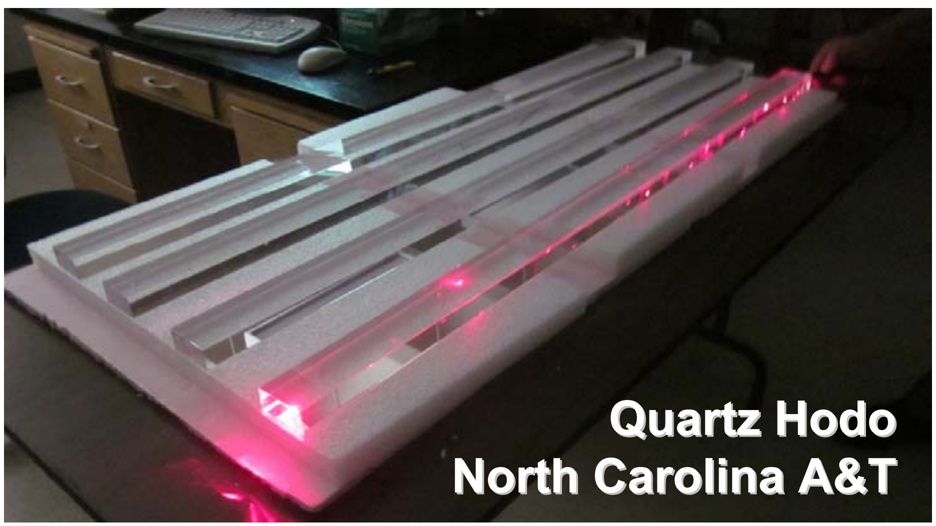
- Super-fast (high x_B) quarks.
- Form factors of simple quark systems.
- The transformation of quarks into hadrons.
- Quark-quark correlations.

SOS Dipole Leaves Hall-C…



…and SHMS Wheels Arrive

SHMS Focal Plane Detectors



SHMS+HMS Scaling Experiment Goals

- **Measure the Q^2 dependence of the $p(e,e'\pi^+)n$, $p(e,e'K^+)\Lambda$, $p(e,e'K^+)\Sigma$ cross sections at fixed x_B and –t to search for evidence of hard-soft factorization**
  - Separate the cross section components: L, T, LT, TT
  - Highest Q^2 for any L/T separation in π,K^+ electroproduction

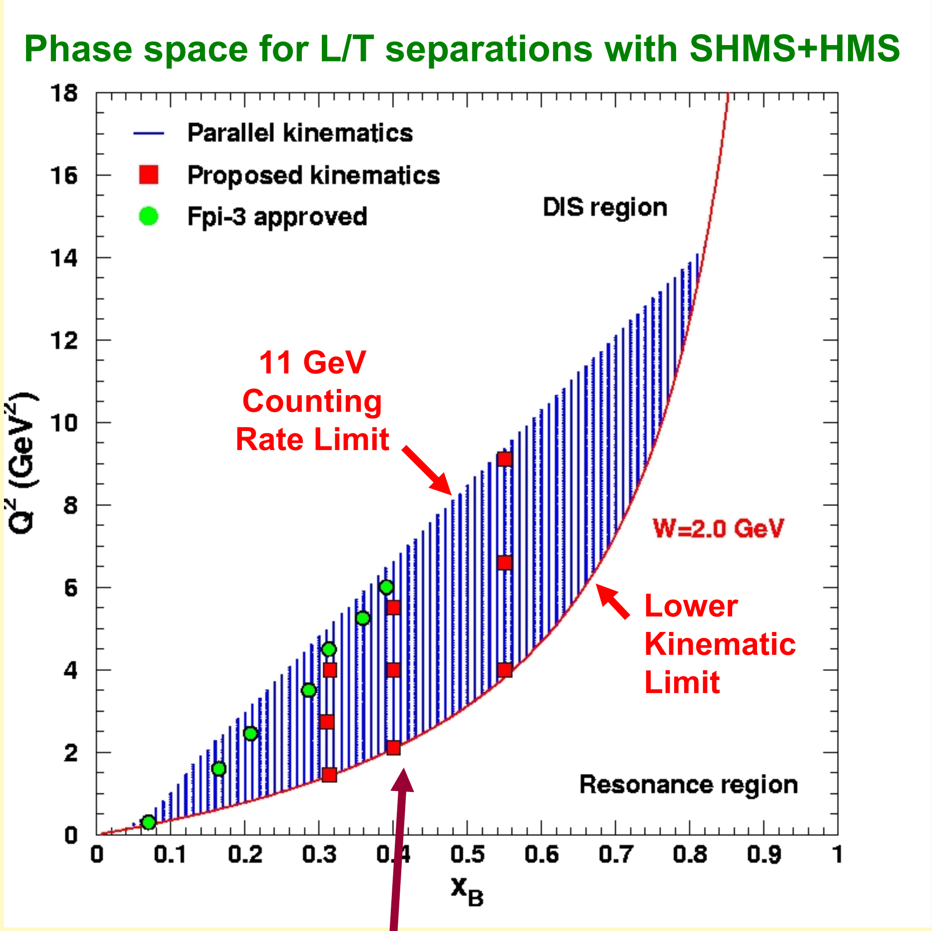
Our theoretical understanding of hard exclusive reactions will benefit from L/T separated pion and kaon data over a large kinematic range

- Quasi model-independent comparison of pion and kaon data would allow a better understanding of the onset of factorization
- Constraints for QCD model building using both pion and kaon data (flavor degrees of freedom)
- Understanding of basic coupling constants (Σ°/Λ ratio)

SHMS+HMS Scaling Experiment Overview

- Measure separated cross sections for the p(e,e'π^+)n, p(e,e'K^+)Λ, p(e,e'K^+)Σ reactions at three values of x_B.
- **Q^2 coverage is a factor of 3-4 larger compared to 6 GeV.**
  - **Facilitates tests of the Q^2 dependence even if L/T is less favorable than predicted.**

x	Q^2 $(GeV/c)^2$	W (GeV)	-t $(GeV/c)^2$
0.31	1.5-4.0	2.0-3.1	0.1
0.40	2.1-5.5	2.0-3.0	0.2
0.55	4.0-9.1	2.0-2.9	0.5



Kinematics for π measurements

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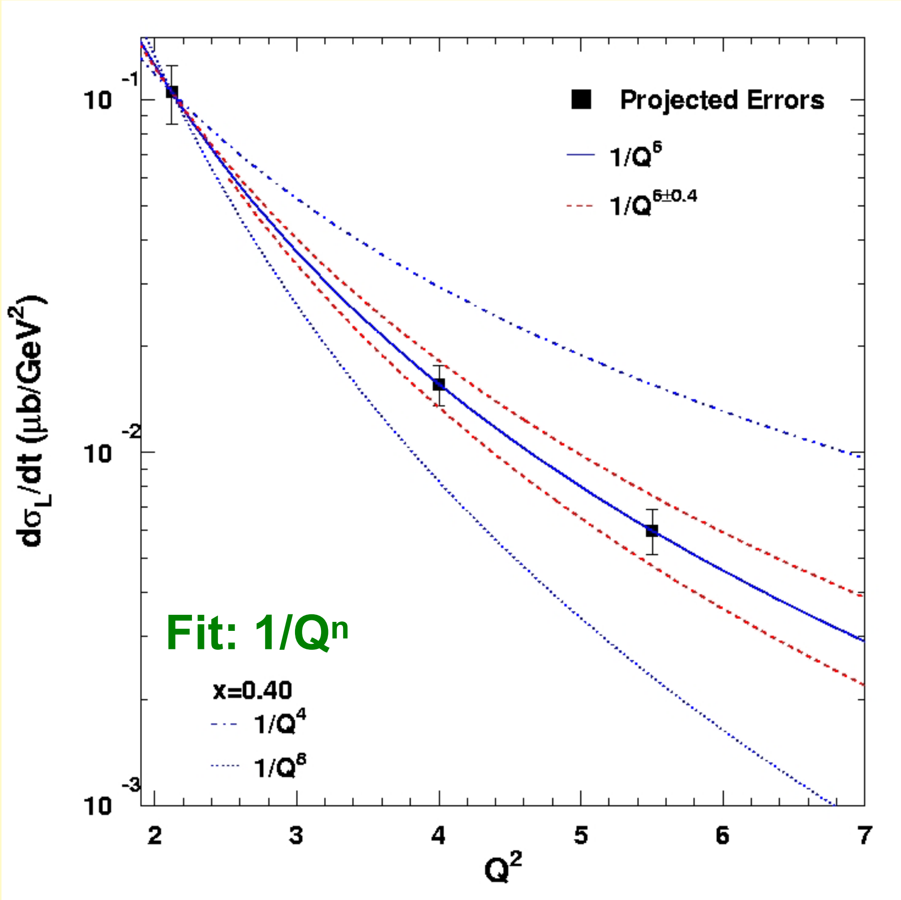
Projected p(e,e'π^+)n Uncertainties for $1/Q^n$ Scaling

QCD scaling predicts:

$\sigma_L \sim 1/Q^6$

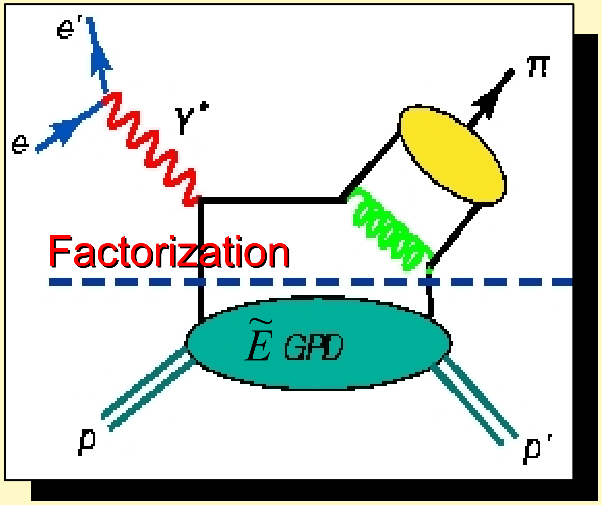
$\sigma_T \sim 1/Q^8$

x_B	dn^L	dn^T	dn^{LT}	dn^{TT}
0.31	0.3	0.2	0.5	0.6
0.40	0.4	0.3	0.7	0.8
0.55	2.5	1.0	-	-



p(e,e'K^+)Λ,Σ measurement scheduled as one of the SHMS+HMS commissioning experiments, to run in 2016-17.
→ First L/T separation involving both spectrometers.

Next Generation Study: Polarized GPD $\tilde{E}$



- **$\tilde{E}$ involves a helicity flip:**
  - Depends on the spin difference between initial and final quarks.

$$\sum_q e_q \int_{-1}^{+1} dx\ \tilde{E}^q(x,\xi,t) = G_P(t)$$

$G_P(t)$ is highly uncertain because it is negligible at the momentum transfer of β-decay.

- **$\tilde{E}$ not related to an already known parton distribution → essentially unknown.**
- Experimental information can provide new nucleon structure information unlikely to be available from any other source.

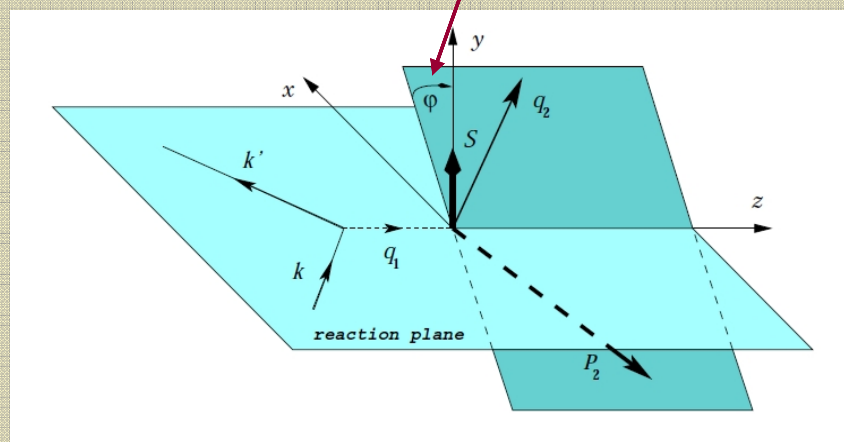
Polarized GPD $\tilde{E}$

- The most sensitive observable to probe $\tilde{E}$ is the transverse single-spin asymmetry in exclusive π production:

$$A_\perp = \frac{\int_0^{\pi} d\beta \frac{d\sigma_L^{\pi^-}}{d\beta} - \int_{\pi}^{2\pi} d\beta \frac{d\sigma_L^{\pi^-}}{d\beta}}{\int_0^{2\pi} d\beta \frac{d\sigma_L^{\pi^-}}{d\beta}}$$

$d\sigma_\pi^L$ = exclusive π cross section for **longitudinal γ^***

β =angle between **transversely polarized target** vector and the reaction plane.



Requires both an L/T separation and a transversely polarized target.
→ Very challenging measurement!

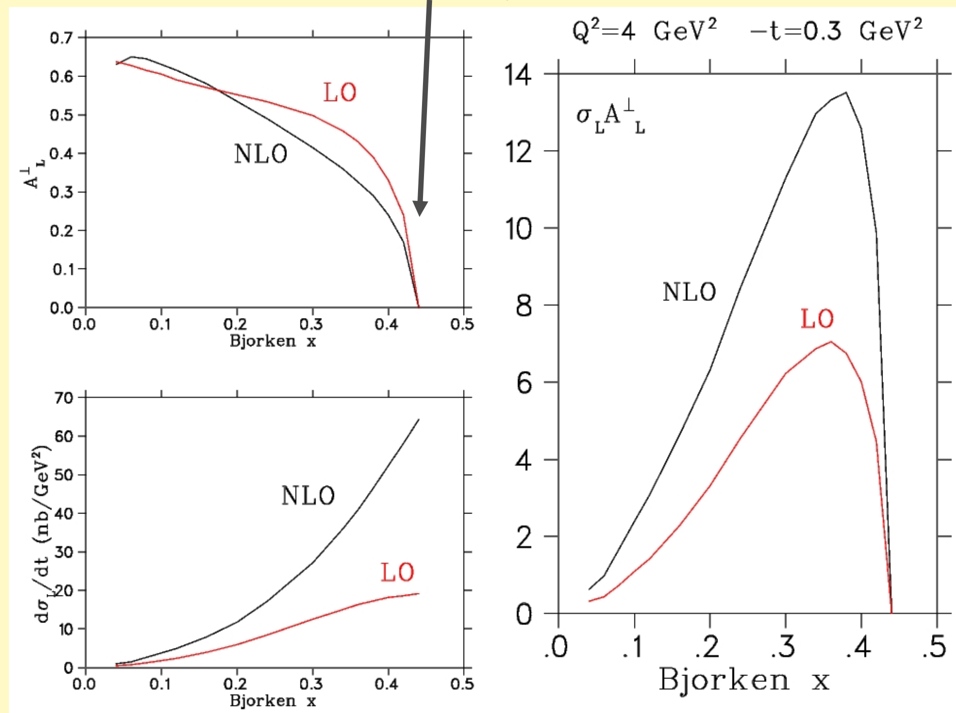
GPD information in $A_L^{\perp}$ may be particularly clean

- GPD formalism is restricted to regime where hard & soft contributions factorize.
- $A_L^{\perp}$ is especially interesting because it is expected to display **precocious factorization** at only Q^2~2-4 GeV^2.
- Argument by Frankfurt et al. [PRD **60**(1999)014010]
  - Precocious factorization of the π production amplitude into three blocks is likely:
    1. overlap integral between γ, π wave functions.
    2. the hard interaction.
    3. the GPD.
  - **Higher order corrections, which may be significant at low Q^2, likely cancel in the asymmetry ratio.**

Cancellation of Higher Twist Corrections in $A_L^\perp$

- **Belitsky and Müller GPD based calc. reinforces this expectation:**
  - At Q^2=10 GeV^2, NLO effects can be large, but cancel in the asymmetry, $A_L^\perp$ (PL **B513**(2001)349).
  - At Q^2=4 GeV^2, higher twist effects even larger in σ_L, but still cancel in asymmetry (CIPANP 2003).

$A_L^\perp$=0 at parallel kinematic limit, where P_y is not well defined.



This relatively low value of Q^2 for the expected onset of precocious scaling is important, because it is experimentally accessible at JLab 12 GeV.

Dr. Garth Huber, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.

L/T Separations Essential to $A_L^{\perp}$

- In hard meson electroproduction, factorization can only be applied to **longitudinal photons**.

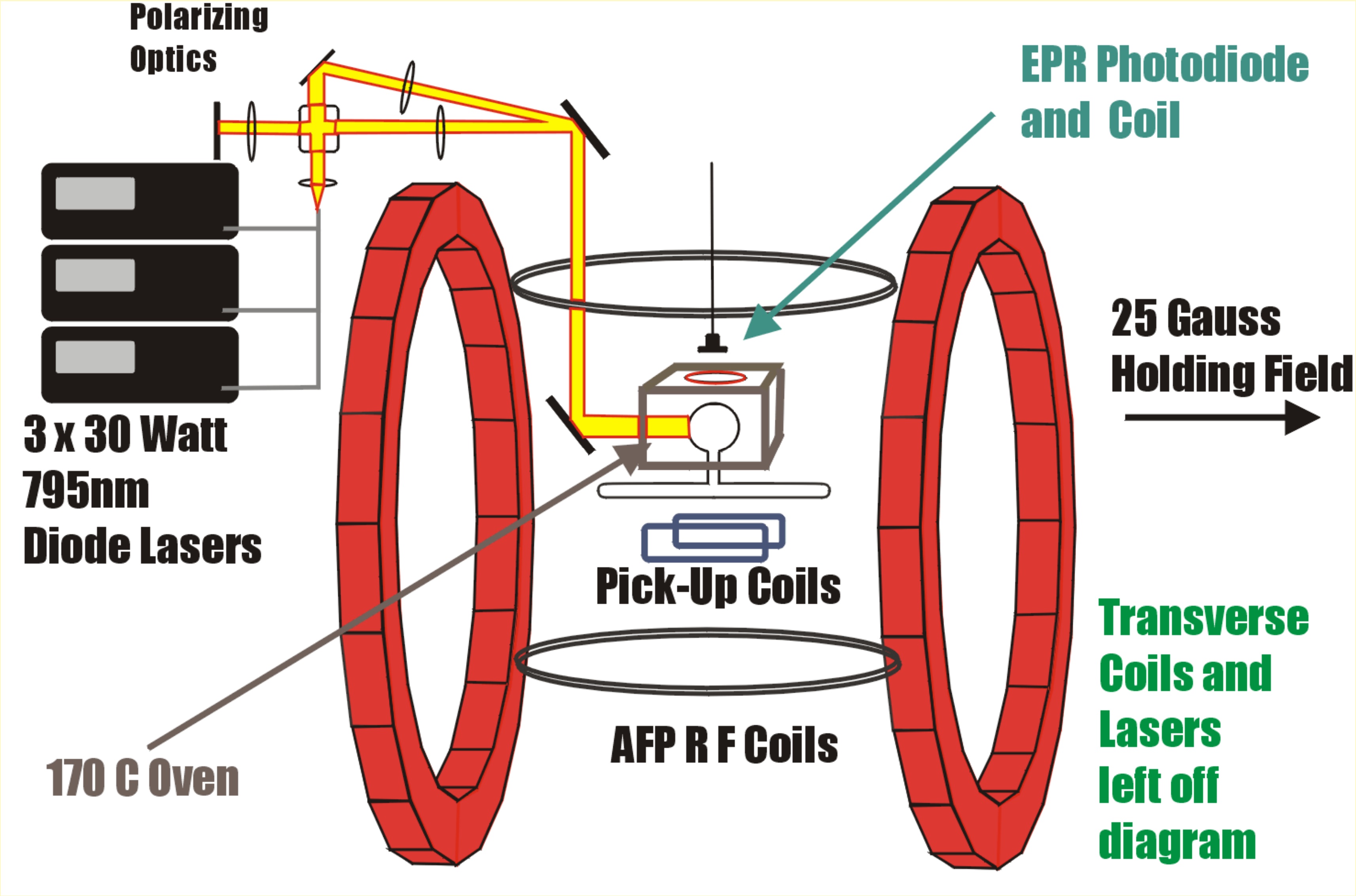
- **Unlike other ongoing or proposed experiments, where dominance of longitudinal contribution is simply assumed, JLab's unique contribution to this field is in:**
  - **ability to take measurements at multiple beam energies.**
  - **unambiguous isolation of $A_L^{\perp}$ using Rosenbluth separation.**

- A JLab $A_L^{\perp}$ measurement could thus establish the applicability of the GPD formalism, and precocious scaling expectations, for other $A^{\perp}$ experiments.

High Luminosity Essential to $A_L^{\perp}$

- **Physics case for a measurement of $A_L^{\perp}$ is compelling.**
- High luminosity required:
  - σ_L is largest in parallel kinematics, where $A_L^{\perp}=0$.
  - σ_L is small where $A_L^{\perp}$ is maximal.
- The measurement has long been considered to be impossible because of the lack of a polarized target that can handle the required high luminosity.
- **Recent advancements in polarized ^3He target technology may allow the measurement to proceed via the $n(e,e'\pi^-)p$ reaction.**

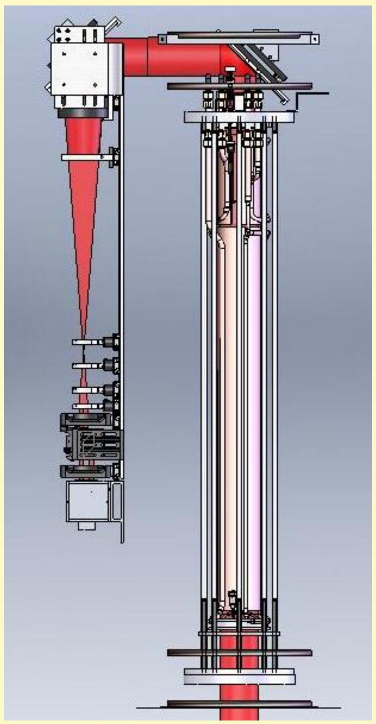
Hall A Polarized ^{3}He Target: FOM(P^2L)=0.22E+36



UNH/Xemed Target Loop Concept: $P^2L=0.55E+38$

- Compress polarized ^3He and deliver to aluminum target cell
- Non-ferrous diaphragm compressor achieves 3000 psi (~200 bar)
- Returns through a pressure-reducing orifice

External polarizer



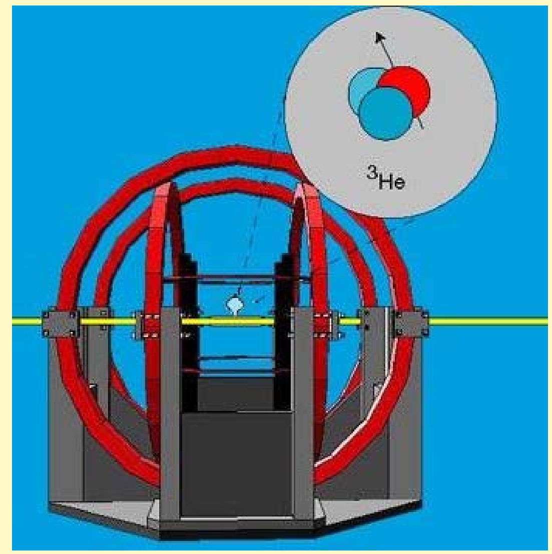
Requires two ports, entrance and exit

20 Bar

Non-ferrous diaphragm compressor

200 Bar

Nuclear physics target



9 cm aluminum target cell
Cooled with LN_2 to 77K
Thickness of 0.5 g/cm^2

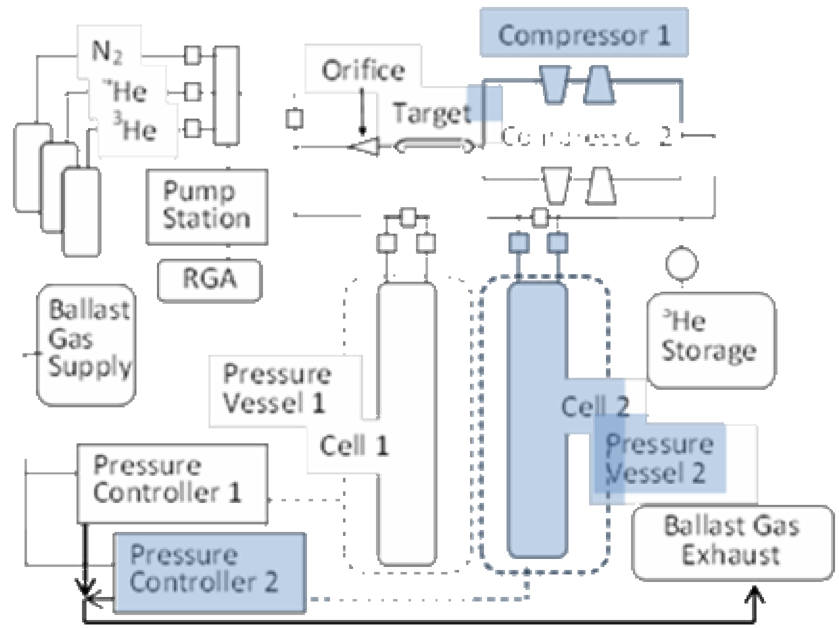
Expansion through an orifice

Recirculates at 25 SLPM

Dr. Garth Huber, Dept. of Physics, Univ. of Regina, Regina, SK S4S0A2, Canada.

^{3}He Polarized Target Rationale

- By providing optical pumping repolarization rates that keep ahead of beam depolarization rates, we propose development of a scalable polarized ^{3}He target system that:
  - provides a ^{3}He target thickness as high as 0.5 g/cm^2 in 10 cm
  - accepts the full 80μA polarized beam current at Jefferson Laboratory, and
  - maintains 65% polarization at luminosity of 10^{38} e-nucleons/cm^2.

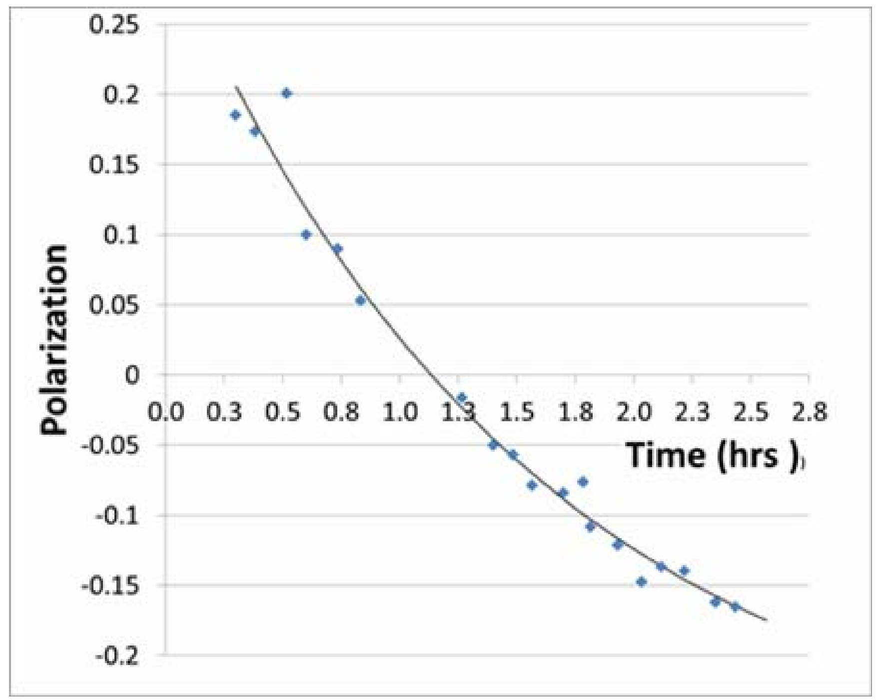


- By relocating critical components of the polarizer system in a loop outside the beam enclosure, we can incorporate redundancy and eliminate single points-of-failure.

Working Large-Scale ^{3}He Polarizer Prototype

Assembled, Operating ^{3}He Polarizer

- 8.5L aluminosilicate glass cell.
- Pressure-vessel enclosure.
- Operation up to 20 atm.
- Hybrid pumping with K:Rb.
- Spectrally narrowed 2.5kW laser.



- Spin-up curve measured by laser-polarization-inversion.
- Spin-up rate ~15%/hr.

April 23, 2012

High Luminosity Polarized ^{3}He Target Status

Many of the hardest technological hurdles have been demonstrated through working prototypes.

1. Large-scale ^{3}He polarizer can operate at temperatures, pressures and laser-beam intensities that replace spins (much) faster than they will be destroyed by the beam at $\mathcal{L}$=5x10^{37} cm^{-2}s^{-1}.
2. Capability to develop and produce industrial-quality compressor pumps from non-ferrous materials.

Next phase of development:

1. Need to demonstrate high polarization (inadvertent contamination has limited asymptotic polarization <50%).
2. Need to make a cell with inlet and exit ports.
3. Need to measure ^{3}He depolarization in a loop that includes pump and orifice.

JLab PAC39 Comments, June 2012

PR12-12-005: *"The Longitudinal Photon, Transverse Nucleon, Single-Spin Asymmetry in Exclusive Pion Electroproduction"*, D.J. Gaskell, F.W. Hersman, G.M. Huber, D. Dutta, Spokespersons

- "The scientific case is really worthwhile. However, in view of many technical issues for this very challenging high luminosity polarized ^{3}He target, the proposed experiment cannot be part of the top half of the priority list of experiments to be established for the first 5 years of 12 GeV operations.

  The PAC encourages the group to purse all these technical efforts to provide a new generation of high luminosity polarized ^{3}He target from which several other experiments can benefit."